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Addressing health and equity in residential low carbon transitions – Insights from a pragmatic retrofit evaluation in Australia

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ABSTRACT

Health and equity present obligations and currently under-realised opportunities in low carbon transitions. Energy efficiency improvements of homes may benefit health and access to affordable energy, yet better knowledge about contextual mechanisms and household practices is needed for the development of effective programs. This paper presents a mixed methods evaluation of a quasi-randomised controlled retrofit trial targeting low-income older householders. Socio-technical systems thinking offered a useful approach to explore the construct of the engineering-dominated concept of residential energy efficiency in combination with the people-focused experience of housing and health. The study combined a phenomenological enquiry into householder practices with quantitative analyses to explain health, energy cost, temperature and psycho-social outcomes for winter.

The findings showed that small retrofits may mitigate the growing energy demands of this ageing population group, provide better comfort and reduce energy costs, but that the effectiveness of the retrofits was reduced by socially shared heating and ventilation practices that contradicted engineering assumptions, the physiological capabilities of the householder and the modes of energy bill payments. A program that is framed around caring and safety and combines retrofits, tariff optimisations and householder practices could provide equitable climate change mitigation outcomes and co-benefits for health for this population group. The paper concludes with implications for the integration of equity and health as goals into low carbon transitions.

1. Introduction

In the context of low carbon transitions, human health could be both an obligation and a driver. By including the right to health and mandating the protection of vulnerable people, the Paris Agreement [1] has drawn attention to the notion that climate change mitigation actions have an ethical dimension and carry moral responsibilities that are often overlooked in low carbon transition theories and practices [2,3]. Although the concept of energy justice is extending the meanings and value propositions of transition frameworks [2,3], considerations of health are still underplayed [2,4,5]. However, there appears to be emerging awareness that, on the one hand, tensions around health in current low carbon transitions strategies require urgent attention [4–10] and that, on the other hand, opportunities for health need to be promoted and acted upon [10–12]. This paper addresses health as an important co-benefit of building carbon mitigation efforts [12–14], and the problem that developing categorical evidence and providing universal recommendations has proven difficult [15–17].

More empirical evidence on the benefits for health is needed to justify energy conservation policies, promote their implementation and to optimise the design of intervention programs to improve householders' health [18,19]. Experimental intervention studies are considered more suitable to inform the question of causality than observational studies [16,20,21], yet the influence of householders on the outcomes of residential energy efficiency improvements is under-researched. As predicted impacts of energy retrofits rarely correspond to real life outcomes [22], more research interrogating engineering-based assumptions and extending nomothetic epistemological approaches is needed. One way to achieve this is by considering the material entity of the building, the activities of the householders and how they interact as a socio-technical system [23–25]. Examples of empirical research into residential energy efficiency improvements using a socio-technical

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approach have been published [26–28]; however, further work that provides in-depth and contextual insights to explain the variability in energy and health outcomes from residential energy efficiency interventions [25] is needed to guide future policy and intervention programs.

The study reported in this paper addressed this gap in responding to the challenge of supporting an ageing population towards a lower carbon, more equitable and healthier future. As well as using a socio-technical framing, a further contribution lies in its pragmatic approach [29–32], which addresses the technical, social and health aspects of residential energy interventions [33]. The research comprised a field trial of residential energy efficiency improvements of the homes of low-income, older and/or frail people living at home with the help of community care services in Victoria, Australia. As in many other developed countries, in Australia older people may experience energy hardship with possible adverse impacts on their health [34–42]. Although energy efficiency retrofits can play a notable role in achieving carbon reduction goals and lower energy costs [43–47], many older Australians lack the capital for such measures [48]. Hence, in keeping with the imperative of the Paris Agreement to safeguard intergenerational equity, health and vulnerable groups, there is an urgent policy need to find avenues to assist this cohort in the transition to a lower carbon society in Australia and beyond. However, assistance requires engagement, which has proven difficult with this population group [49,50]. This study addressed both accessing older people and implementing retrofit interventions.

This paper is structured as follows. Section 2 sets out the conceptual framework of residential energy efficiency and health as a socio-technical system. Section 3 describes the methods of the study. Section 4 presents the findings in six subsections related to householder practices. Section five provides the illustration and description of the system revealed in this study. Section 6 discusses the findings in relation to the literature or residential energy interventions and outlines the implications of this research for a transition to a lower carbon, more equitable and healthier future beyond Australia.

2. Residential energy efficiency and health as a socio-technical system

Socio-technical systems are material, conceptual or symbolic constructs that are characterised by the links between humans and materials, machines or technologies [51]. Systems are dynamic, and the impacts of change may not follow rules of linearity or proportion [52]. The theoretical concept of socio-technical systems has been transferred to a number of relevant contexts, including to the interaction of buildings and occupants [53], the concept of negotiated comfort [54,55], practices around energy consumption [56], and into frameworks illustrating the relationship between housing risk factors and ill health [57–59].

Social practices studies may enhance socio-technical transitions models to a low carbon future by highlighting the role of users [60,61]. Social practices are activities regularly performed by people over space and time with shared social or cultural meanings [62,63] and using particular materials and skills [64]. Hence, in social practice theories, the focus of enquiry is on practices as expressions of collective knowledge, meanings and understandings [62,64]. Drawing on the prevalent definition of social practices in research on the built environment and energy consumption by Shove, Pantzar and Watson [64], social practices are here understood as activities that are bound by the elements of material, meanings and competences. Social practice theory acknowledges that engineering-based predictions rely on assumptions that do not take into account that a dwelling is also a home with multiple and constantly evolving meanings, that householder may not be the rational actors assumed in many transition theories and, hence, that the management of transitions is a difficult and often biased undertaking [65]. By focussing on the dynamic recursive interactions of structural, social, spatial and temporal conditions, social practice theories offer an alternative to the conventional attention to individual, intellectual or economic choices in managing the transitioning to a less fossil-fuel reliant society [63,66].

The link between everyday practices and health has been acknowledged in recent calls for a reconceptualization of the definition of health and the emerging capabilities approach to energy poverty. There seems to be agreement that the concept of health is multifaceted and relative, that coping capacities need to be acknowledged, and that effective health promotion cannot only rely on individual self-management but needs to take a systems approach that considers contextual determinants [67,68]. Similarly, the capabilities approach to fuel poverty promotes an assessment that acknowledges meanings as shaped by contextual conditions and the legitimacy of human adaptation and coping strategies [69]. The reconceptualisation of health as a process and the shift in focus to adaptation concur with the critical realists' view adopted in this study that householders are not "physiological dopes" [70], and that contextual considerations may help in explaining the variability in energy and health outcomes from residential energy efficiency interventions [25].

Residential energy efficiency describes the amount of energy that is needed or consumed for the useful services of every day practices at home. In Australia, residential energy efficiency ratings are determined by the Nationwide House Energy Rating Scheme (NatHERS) and expressed as stars. The more stars the home is awarded, the better its thermal performance is expected to be. The simulation engine calculates the transient heat gains and losses taking into consideration the thermal performance of the building envelope, thermal storage, orientation, latent and sensible internal gains, cooling effects from cross ventilation and ceiling fans, hourly weather data and typical occupant behaviours [71–74]. Air permeability rates and provision, efficiency or location of space conditioning systems are not prescribed. Currently 6 stars are the minimum rating for new homes and major alterations. It is estimated that 86 per cent of all existing homes in the state of Victoria, the location of this research, only have an energy efficiency rating of 1.8 stars [75], which is predominantly achieved through roof insulation. These home energy ratings are based on the design of buildings. However, social scientists have pointed out that the energy efficiency of a building is dependent as much on the material quality of the building and its appliances as on the householder practices of energy consumption [23,24,76–78].

3. Method

In keeping with calls for multi-disciplinary and multimethod research when investigating socio-technical relationships [79], this mixed methods research was situated at the confluence of the disciplines of building physics and social sciences and embedded within public health research. Informed by critical realism [80], this study evaluated a quasi-randomised controlled field trial of residential energy efficiency improvements of the homes of low-income home care recipients near Melbourne, Australia. Home care services offer domestic cleaning services, home maintenance and modification for better accessibility to support older Australians who live independently. This research was an addition to the Energy Saver Study (ESS) by the South East Councils Climate Change Alliance (SECCCA) [81].

The primary research question was: How does knowledge of the householder lived experience of the retrofits contribute to a better understanding of possible impacts of residential energy retrofits on the health of older and/or frail householders in Victoria, Australia? The objective was to quantify changes in indoor temperatures, energy consumption, energy costs and health due to the ESS building retrofits, to explore the experience of the householders, and to identify householder practices and their preconditions that appear to have influenced the mediating factors along the pathway from improved energy efficiency of the building to health outcomes [17,25]. A social practice

approach was adopted to provide an understanding of how the material entity of the dwelling, householder competences and the meanings of practices shaped the health-related outcomes and the health of householders. Hence, a quantitative evaluation and a phenomenological study were undertaken concurrently for the purpose of complementarity [82]. This approach promised the explanation of the main health-related outcomes of warmth, affordability of energy and householder satisfaction as well as a better understanding of the contextual influences and preconditions of householder practices.

3.1. Recruitment, intervention and data collection

The partner organisation SECCCA recruited 30 households, allocated them quasi-randomly to the study groups and implemented the energy efficiency intervention in the intervention group. The retrofits consisted of the replacement of light bulbs with LED lights, top-up R4 ceiling/roof insulation and draught proofing, with one home also receiving a new reverse cycle air conditioner (RC AC). Independent actions comprised two new RC ACs and a new ducted evaporative cooling system in the intervention group and two new RC ACs and a new portable electric heater in the control group. Control group households received a retrofit at the end of the study period.

The trial as an adjunct to the ESS was approved by the authors' university's ethics committee, and written consent forms were used. The various data collection and analytical methods as well as sample characteristics are described in more detail in companion publications [38,83,84] and summarised here. Data were collected before and after the retrofit interventions in the spring of 2014 and 2015. Quantitative data, which included the homes' energy efficiency ratings, Blower Door Test results, householder demographics and half-hourly time-stamped indoor temperatures, electricity and gas consumption data were collected as part of the ESS and provided by SECCCA. For the comparison of absolute values of energy consumption and indoor temperatures, the data was standardised to 'average' winter days with a daily mean outdoor reference temperature of 10^0C [85]. Researcher-administered householder surveys, including the participants' perception of comfort temperatures, and face-to-face, semi-structured interviews were the main methods of primary data collection of this adjunct study.

3.2. Data analysis

Monitored data were standardised to mean values for average winter days with daily mean outdoor temperatures around 10^0C [83,84]. Differences in quantitative changes between the groups were calculated to assess 'what worked' according to statistical, practical and clinical significance [86]. The statistical significance expressed if there was less than a five per cent probability that the observed effect was due to chance and was determined by non-parametric Mann-Whitney U-tests comparing the mean ranks of the changes within each group. The mean values are presented in the results section to facilitate the comparison of outcomes to other studies and to assess practical significance.

The practical significance of the quantitative outcomes, as expressed by the effect size, indicated the importance of the outcomes for the practices of climate change mitigation and improving social equity or health. Practical significance can add meaning to quantitative outcomes when small sample sizes make it difficult to find statistical significance [87]. Even weak effects may be valuable, when there are no risks or the outcome is death [88]. A value of $r > 0.10$ was interpreted as a small effect, $r > 0.30$ as medium effect and $r > 0.50$ as a large effect [89]. Any reductions in greenhouse gas emissions, decreases in cold, reduction of energy costs, improved psycho-social benefits and better health were considered meaningful benefits for the environment and the participants.

Clinical significance, which means an improvement in outcomes to normative levels in individual households, was assessed in terms of the subjective outcomes in comfort, affordability of fuel and underheating of living rooms and bedrooms. Clinical significance addresses the "extent to which an intervention makes a real difference to the quality of life of the participants" [86]. Hence, clinical significance acknowledges the relevance of the individual's perspective in the evaluation of an intervention and proposes normative comparisons [90]. On the premise that there is a general consensus that being able to afford heating to adequate indoor temperatures is a basic necessity [91,92], improvements in follow-up scores that implied feeling comfortable, being able to heat the home adequately, not having to compromise on heating and the elimination of underheating were considered clinically significant.

The conversations during the administration of the surveys and the semi-structured interviews about the participants' homes, health and everyday routines were audio-recorded and transcribed verbatim. Conversation analysis [93] was used to highlight how the participants' interacted with other members of the household and with the researcher during household visits. The interviews were analysed thematically to identify key practices that were shared among households and to establish their pre-conditions and meanings as well as the participants' interpretation of their own capabilities, the retrofit outcomes and the study processes. To this end, the first four interviews were coded into topics or 'nodes' without a framework using topical, or constant comparison analysis [93]. After reflecting on these nodes, mother nodes were created, and all nodes were structured into a nodal tree, showing how the nodes related to one another. The nodes reflected the sorting of the data into categories of heating, cooling, ventilation, paying bills, coping and adaptation practices. Additional nodes were created to collect the meanings of the practices and lived experiences, householder competency and material aspects of householder practices. Repeated ideas, practices or meanings became themes. Discourse analysis [93], based on idiosyncratic uses of language, was used to develop themes and highlight patterns around 'what mattered' to the participants and the meanings given for their practices. The mother nodes, or main themes were partially quantified [94] by determining the frequency and prevalence of responses.

3.3. Strategies to attain research quality

Strategies were implemented to attain validity of the quantitative research component, trustworthiness of the qualitative research components and legitimation of the mixed methods inferences. With regard to the quantitative components of the study, external validity was ensured by checking the presence of retrofit measures that had been reported by SECCCA on site and by asking householders at each visit if they had made any changes 'in and around' their home. Householders were also asked if they had made any changes to heating their homes and to the opening of windows and doors, in order to control for possible changes in practices. Internal validity of indoor temperature measurements was ensured by checking the correct placement of data loggers, by comparing photographed logger readings at the time of the interviews with those supplied to the researcher, and by careful data cleaning of days of householder absences. Monitored energy consumption data was validated by comparison to billed consumption data. Star ratings and Blower Door tests were only performed by accredited professionals. SF36v2 survey data was checked and prepared according to published guidelines. Statistical procedures were checked with the university's statistical consultation team.

Reliability was ensured by keeping a log book on the analytical procedures in general and by noting any changes, corrections, developments or further analyses of specific variables. Replicability of the calculations is possible as all data have been stored and detailed records on how the data was prepared, standardised and analysed have been kept. It would also be possible to reproduce the experiment, as detailed information on intervention measures, instrumentation and surveys have been stored. However, it would be impossible to replicate or reproduce the results of the intervention due to the inevitable contextual

influences that characterise social field research. The generalisability of the quantitative findings of this study (that is, drawing conclusions from the results of these 29 households to the Australian older population in general) was limited by the small sample size. Analytical generalisability was sought through inference in the mixed methods framework.

Credibility was supported by structuring the interviews from general questions on the householders and their home, to the more focused topics around warmth and affordability, participant perceptions and interpretations and, at the end of the interview, to open comments by the householders. The study scheduled repeated visits to households to establish trust and to gain familiarity with the dynamics of the participants' daily lives. All participants in the sample were interviewed to capture the multitude of experiences and to provide representative outcomes for this cohort. Verbal data was complemented by field observations. Honesty in the participants' responses was sought by repeatedly pointing out that the answering of questions was voluntary, by assuring the participants that there were no right or wrong answers, and by stressing that the researcher was interested in the participants' opinions and experiences. In addition, the survey and interviews contained doubled up or iterative questions to detect possible bias. The first author kept reflective notes during the interview and data analysis periods to develop understanding and note insights on the settings of the interviews. Regular meetings of the research team and occasional exchanges with the ESS project team were used to discuss and validate themes that were developed from the interviews by the first author.

Transferability was attained by providing contextual information on the sample households, their expectations, experiences and perceptions, and by thick descriptions. Information on the number and characteristics of the dwellings and households, number of data collection waves and periods and data collection methods has been presented. Dependability was attained by documenting the research design, its implementation, data collection and by reflecting on the limitations of the study and its findings. Confirmability was sought by justifying and explaining the chosen methods, by pretesting the interview questions and surveys in a pilot study, by describing iterative processes, by critically reflecting on the suitability of certain questions based on the responses of householders, and by providing the second and third authors with evidence in the form of bundled quotes for themes and conclusions. The anonymity of participants was protected by using pseudonyms when extracts of the interviews were published.

Legitimation of the mixed methods research approach was sought in the fully integrated mixed method research approach and the strategies to establish quality of the data, interpretative rigour, inference transferability, reporting quality, synthesisability and utility [95]. Fig. 1 shows the quality framework for the fully integrated nature of the research. The conception of the research was based on a realist review of residential energy efficiency interventions [17,25], a manifestation of the early integration of the two methods at the foundational stage, which resulted in the conceptual framework of pathways and explanatory mechanisms. This framework was instrumental in formulating the research question. The research purpose, questions and objectives integrated both quantitative and qualitative enquiries. The rationale of the integrated study was rooted in the pragmatic approach of 'what works' [33] to inform effective retrofit interventions. The mixed methods design was chosen for the complementary nature of quantitative and qualitative techniques [96], to identify householder practices and their contributing elements and to measure and explain outcomes. Integration continued during the simultaneous data collection, analysis and interpretation stages of the study. Planning and design transparency of the fully integrated mixed method study was established in the detailed description of the pragmatist approach, data collection and analyses.

A concurrent mixed methodological analysis, in which equal priority was given to both data types, was performed in six stages. Qualitative data explained quantitative results; quantitative results developed new qualitative enquiries. To attain rigour in the sequential components, the quantitative and qualitative component were analysed separately up to the point of interface. Interpretive rigour [95] was attained by distinguishing the findings of each method, by exploring the diversity of outcomes, and by comparing the findings of this study with that of others. This study aimed for population transferability, for the translation of the findings of this small cohort to the larger group of low-income, older or frail householders in Victoria. As this study represented an initial foray into the influence of householders in Australia on building performance and health, further studies may wish to compare their findings with the results of this work, to establish commonalities or differences and their reasons. Some peer scrutiny was attained by discussing the findings of the Health Study with the ESS project team as well as with researchers from other LIEEP projects at a forum in May 2016.

Reporting quality was sought by reporting and justifying each aspect of the research process. Academic journal and conference papers have been prepared to showcase the mixed methods and to disseminate the findings. Synthesisability of the results of this study within the context of LIEEP was limited, as the purpose of this health-focused study did not match that of the LIEEP program. Synthesisability of the outcomes in reviews is supported by the comprehensive reporting of analytical procedures and outcomes. The utility of the study lies in the in-depth approach of the case study and in the identification of diverse householder practices. These findings have been interpreted for their implications for policy and practice.

4. Results

The final sample comprised 13 control and 16 intervention households (Fig. 2). The typical home in both groups was a brick veneer house on a concrete slab with less than 11 cm of ceiling insulation and single glazed windows (Fig. 3). All homes had either central heating or a room heater in the living room. The average house sizes were similar for the two study groups around 140m^2. The typical participant was an older female owner-occupier, who lived with her husband on a low income, occupied the home the whole day and indicated a long-standing illness or disability [83].

The intervention lifted the mean star rating of the intervention group homes by 0.8 stars to 3.5 stars (Fig. 4). The draught proofing improved the air tightness of the intervention homes from a poor rating with a mean air change rates at 50 Pa (ACH50) of 20.5 1/h to a fair rating of ACH50 14.4 1/h (Fig. 5).

The main themes derived from the qualitative data were 'keeping warm', 'affording energy' and 'maintaining good air quality', which formed part of the practices of' 'living at home' and 'staying healthy'. Explanations of 'how', 'why' and 'what mattered' explained how householder practices influenced the quantitative outcomes, how these practices were shaped and the meanings of participation in the study [84].

4.1. Keeping warm

Valid indoor temperature data was available for 12 living rooms and 12 bedrooms. At the baseline, all living rooms were heated for some time during the day. The analysis was not able to provide evidence for statistically significant benefits of the intervention measures on various indicators of living or bedroom warmth. However, the daily mean living room temperatures on average winter days in intervention homes rose by an average net 0.71^{0}C compared to the control group with a small size effect (Fig. 6).

For this population group, living room temperatures above 18^{0}C are recommended [97]. The intervention appeared to have resulted in only a weak benefit in reducing the exposure of householders to inadequate living room temperature levels during awake hours (net benefit of 46 min; not statistically significant) (Fig. 7), as many householders

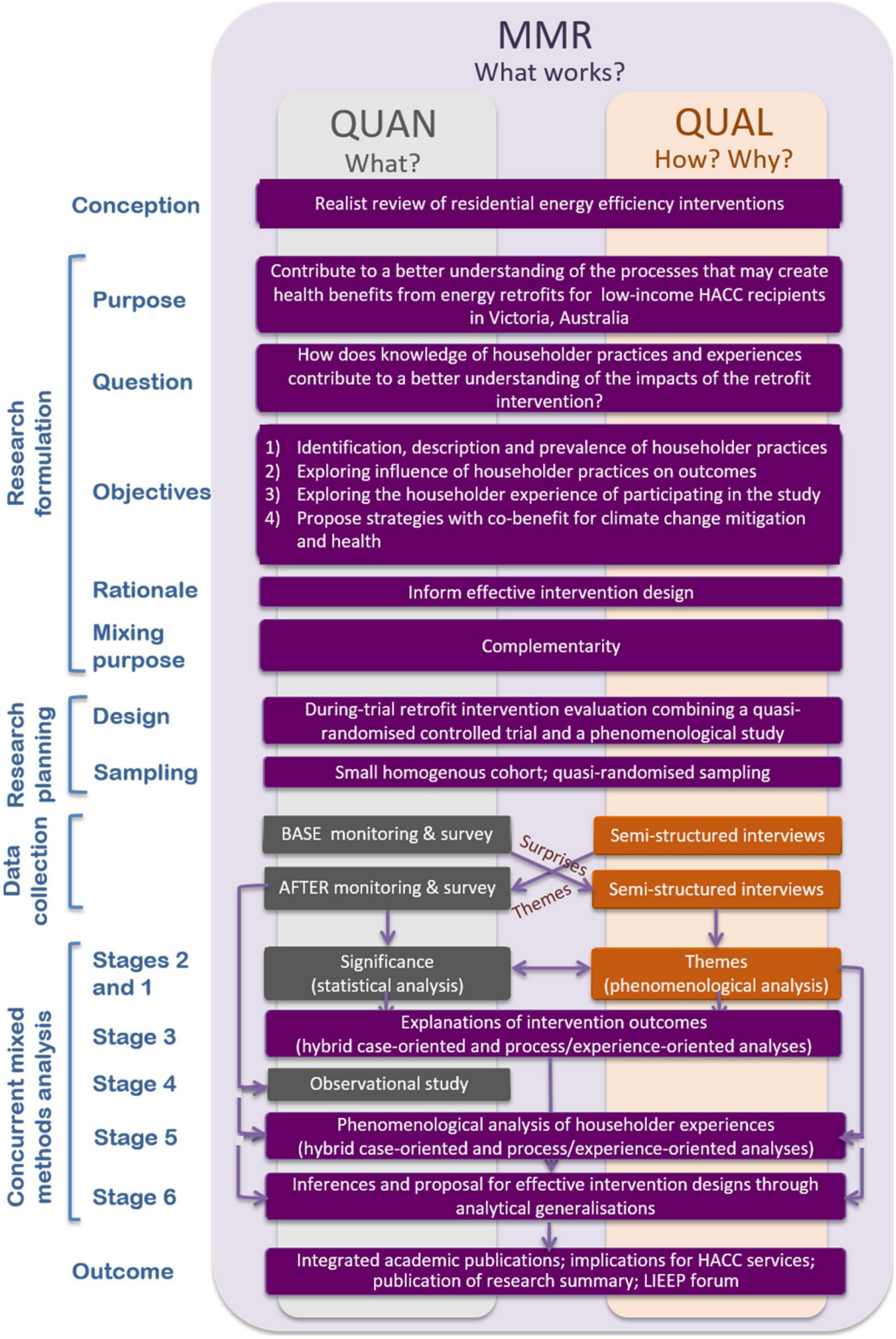
MMR
What works?
QUAN
What?
QUAL
How? Why?
Conception
Realist review of residential energy efficiency interventions
Research formulation
Purpose
Contribute to a better understanding of the processes that may create health benefits from energy retrofits for low-income HACC recipients in Victoria, Australia
Question
How does knowledge of householder practices and experiences contribute to a better understanding of the impacts of the retrofit intervention?
Objectives
1) Identification, description and prevalence of householder practices
2) Exploring influence of householder practices on outcomes
3) Exploring the householder experience of participating in the study
4) Propose strategies with co-benefit for climate change mitigation and health
Rationale
Inform effective intervention design
Mixing purpose
Complementarity
Research planning
Design
During-trial retrofit intervention evaluation combining a quasi-randomised controlled trial and a phenomenological study
Sampling
Small homogenous cohort; quasi-randomised sampling
Data collection
BASE monitoring & survey
Surprises
Semi-structured interviews
AFTER monitoring & survey
Themes
Semi-structured interviews
Concurrent mixed methods analysis
Stages 2 and 1
Significance (statistical analysis)
Themes (phenomenological analysis)
Stage 3
Explanations of intervention outcomes (hybrid case-oriented and process/experience-oriented analyses)
Stage 4
Observational study
Stage 5
Phenomenological analysis of householder experiences (hybrid case-oriented and process/experience-oriented analyses)
Stage 6
Inferences and proposal for effective intervention designs through analytical generalisations
Outcome
Integrated academic publications; implications for HACC services; publication of research summary; LIEEP forum

Fig. 1. Quality framework of the fully integrated mixed methods study.

continued to switch off the heating during the night. Cold homes in the mornings were considered normal, and most householders saw heating as a reaction to cold rather than as a preventative measure. Indoor temperatures were seldom monitored, but some householders regularly checked the barometers on their weather stations to plan their laundry. Some householders had developed adaptation strategies to avoid the morning "chill" or "bite", such as going back to bed after having switched on the heater. The biggest relief from underheating was found in one intervention and one control home, in which participants had felt colder in the follow-up winter due to acute pneumonia and reduced thermoregulation and heated the home for longer.

Overheating of the living rooms to levels above 24^{0}C [98], which may be interpreted as a waste of energy, rose in the intervention group (net 78 min; not statistically significant) (Fig. 8) due to uncontrolled operation of heaters with manual control dials or inauspicious locations of the thermostats of central heating systems in colder locations in the

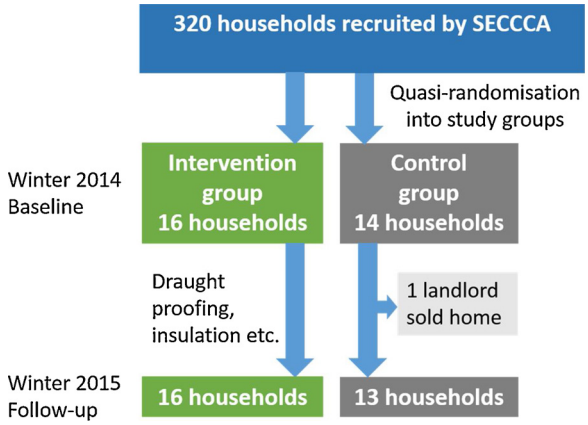

Fig. 2. Flow of households through study.

houses.

The health-relevant benefits of the intervention on bedroom warmth appeared to have been more pronounced. Only half of the bedrooms with valid pre- and post-intervention data were heated at the baseline. The intervention had no effect on daily mean bedroom temperatures on average winter days from pre- to post-intervention winters (Fig. 9). However, the retrofits appeared to have resulted in a reduction of exposure time to temperatures below the recommended 16^{0}C [98] during sleeping times in the intervention group's bedrooms by a net average of 49 min with medium size practical, but not statistically significant effect (Fig. 10).

The better warmth in the intervention bedrooms was attributable partly to higher evening temperatures and partly to reduced heat loss during the night due to the improved ceiling insulation. Householders desired more warmth in their bedrooms, due to increased cold sensitivity or acute health problems. They intentionally left the door of the unheated bedrooms open to the heated living room, used an additional new portable heater or used the central heating for longer periods. However, the practice of keeping a bedroom window slightly ajar (Fig. 12) appeared to inhibit a gain in daily mean temperatures in the intervention bedrooms (Fig. 11).

About half of the participating householders kept windows or doors in the house permanently open to accommodate dogs, avoid mould, improve breathing, mitigate feelings of claustrophobia or due to having grown up sleeping on enclosed verandas, so-called 'sleep-outs':

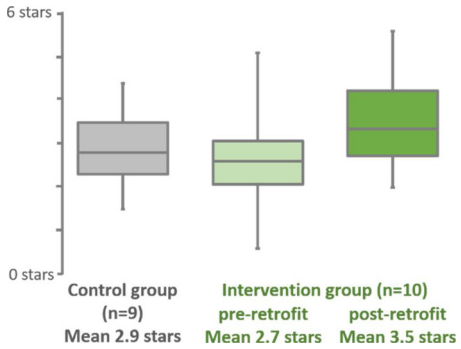

Fig. 4. Home energy efficiency star ratings in relation to study groups and study periods.

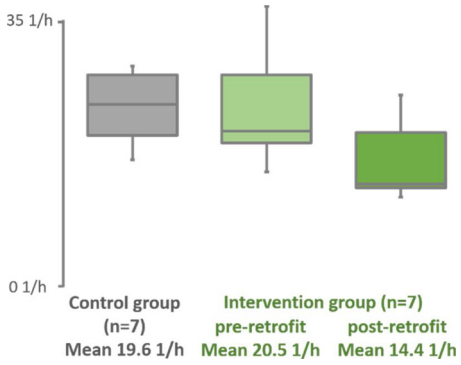

Fig. 5. Measured air change rates in relation to study groups and study periods.

> It's just something I was brought up with. And I always had the windows open to let the fresh air in. I mean not in the middle of winter, although I do leave it a tad, just to let air in, so. I find that if I'm in an area that is closed up I'm certain to become -, I get palpitations and can't breathe, so… (Noeleen, age 75, intervention group)

Exposure to temperatures below guidelines in particular in the mornings was and remained a common problem (Figs. 13 and 14). Many householders persisted in heating only to "take out the chill" and let themselves be guided by subjective comfort levels, the fear of unaffordable energy bills and the perceived norm of intermittent heating.

Fig. 3. Street front of a typical house. Source: First author.

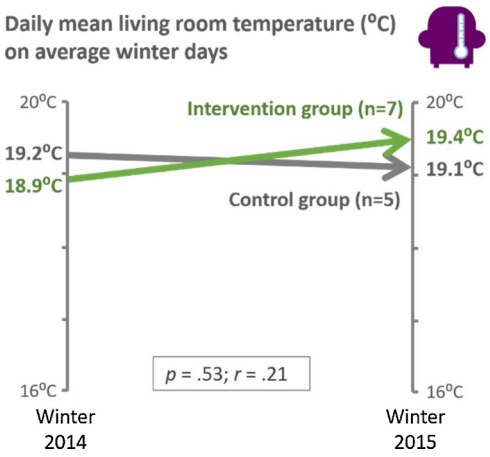

Fig. 6. Changes in daily mean living room temperature on average winter days.

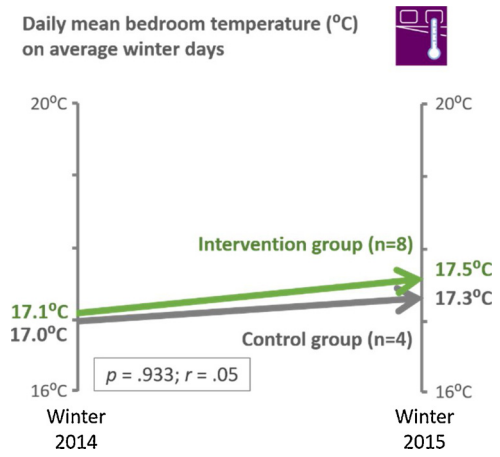

Fig. 9. Changes in daily bedroom temperature on average winter days.

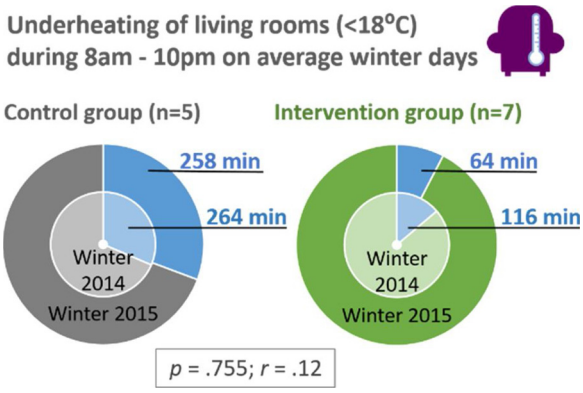

Fig. 7. Changes in underheating of living rooms, when the temperature dropped below 18 °C between 8am and 10 pm on average winter days.

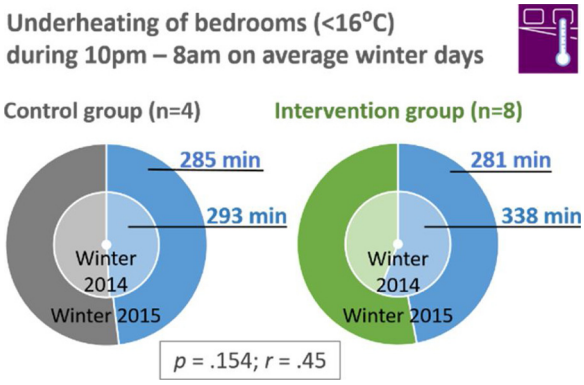

Fig. 10. Changes in underheating of bedrooms, when the temperature dropped below 16 °C between 10 pm and 8am on average winter days.

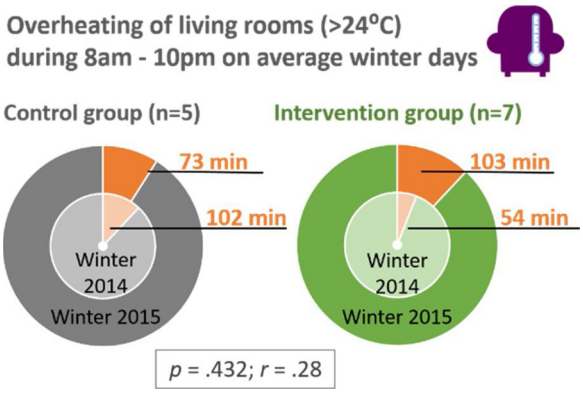

Fig. 8. Changes in overheating of living rooms, when the temperature rose above 24 °C between 8am and 10 pm on average winter days.

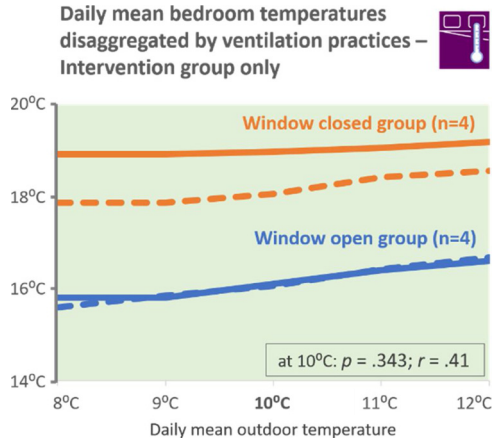

Fig. 11. Daily mean bedroom temperatures before and after the intervention disaggregated by ventilation practices – Intervention group only.

Householders protected themselves from cold exposure through coping and adaptation practices.

> The coldest part is around about five to seven in the morning. We got to trot out to the toilet. [laughs] Old people. [Laughter] So, I turn that [small electric fan] heater on to low. We don't put it on high. Just to take the bite out of the air. [Then the couples goes back to bed]. Sometimes, we'd sleep through till about eight. We get a bit lazy. [Laughter] (Larry, age 83, control group)

Some of these coping practices presented health risks. For example, a sheet or textile 'snakes' at the bottom of doors for draught proofing presented tripping hazards (Fig. 15), an unflued gas heater caused air pollution, and fan heaters next to wash hand basins presented electrical risks (Fig. 16) [83].

The study also found that many householders were able to accept cold mornings, cold bedrooms and their own coping practices with humour as they were not regarded as being particularly unusual. Voluntary underheating, i.e. little heating that was not due to financial constraints, was found in three homes. Continuous heating of the house during the day and night was only practiced in two homes with central heating, in one case to provide comfort, in the other to support muscle function in the mornings. The intervention did not appear to have eased

Fig. 12. Example of open window in the bedroom of an intervention home in winter. The mattress at the bottom had been placed in front of the window for insulation. Source: First author.

the unevenness of warmth between the rooms in the evenings, which reached 9.6^{0}C in the worst case, as householders persisted to give priority to heating of the living rooms and due to parallel increases in warmth in both rooms. This continuance of unevenness may have presented a health risk. However, the intervention gave householders more confidence in the affordability of their heating and perceived achievement of comfort:

> Perhaps I'm a little bit more liberal now because I think, well, the house is better insulated, and I'll just turn the heater on a little earlier, when it is still warmer. (Sarah, age 55, intervention group)

Heating practices as determined by meanings of affordability and comfort, such as carefree heating, careful heating, compromising on heating, struggling to achieve warmth and heating without achieving warmth were identified [38]. The study found a statistically significant positive shift in heating practice classification in the intervention group. Clinical significance was found in five intervention homes and one control home with an independently installed new reverse cycle air conditioner, with householders feeling that they no longer had to compromise on heating (Fig. 17). During the follow-up winter, not being 'able to adequately heat the home' statistically significantly predicted colder bedrooms with large practical significance ($p = .002$, $r = .57$).

4.2. Affording energy

At the baseline six of the 29 homes that remained in the study reported to not being able to heat their homes adequately in winter. Most of these householders (83.3%) felt fuel poor as defined by reported inadequate heating due to fuel costs. The retrofit measures eased subjective fuel poverty in winter, as 'feeling fuel poor' was removed in the intervention group in the follow-up winter (Fig. 18).

Objective changes in energy costs were calculated from the monitored energy data. Time-stamped gas consumption data was available for 26 homes and electricity data for all 29 homes. Most homes used natural gas for heating. The practice of 'going north', i.e. spending some time in the warmer climate in Queensland, was an effective strategy for reducing total energy costs in two homes over winter with benefits for the participants' social health, as they reported to meet up with friends. However, householders were not spared cold related illnesses. Participants reported that inadequate heating in the car or in the holiday accommodation had made them sick.

Taking only occupied days of the home into account, the retrofit intervention statistically significantly reduced the consumption, and hence costs and greenhouse gas emissions from electricity, but not gas, over winter (Fig. 19). These benefits were primarily attributed to the replacement of light bulbs with LED lights and of portable electric heaters with new RC ACs.

Using the standardised gas and electricity consumption indices, the calculation of the heating energy considered that the various mixes of fuels for heating and hot water as well as the types of appliances, and that these had changed from the baseline to the follow-up year in a few cases. Centrally heated homes used about three times more heating energy per day than homes with only a room heater in the living room. The study saw no effect on the percentage changes in mean daily heating energy consumption on average winter days. The reductions in the heating energy costs and greenhouse gas emissions in the intervention group, based on the days that the homes were occupied, were of practical significance with small size effects though not statistically significant (Fig. 20).

The use of auxiliary heaters to provide warmth continued during the study period. In one home, a new electric portable heater in the bedroom in response to increased cold sensitivity led to higher bedroom temperatures and higher heating energy consumption. The biggest percentage increase in heating energy consumption on days on which the home was occupied was 38 per cent. This increased heating was a response to the husband's pneumonia in the second winter and led to more adequate temperatures throughout the day. This so-called the prebound effect [99] was observed in nine intervention homes. In homes, where portable electric heaters were replaced by more efficient RC ACs in addition to insulation and draught proofing, the heating energy consumption on average winter days dropped by at least 12 per cent.

The study found that affording energy was dependent on more than just energy consumption and income, namely on the type of contract, the payment mode, the budget available for energy costs after the payment of medical expenses and availability of savings or "nest eggs". Changes in energy bill payments were able to ease the perceived burden of energy costs irrespective of the intervention. Most householders received governmental energy concessions, yet awareness of these offers was poor, and five eligible householders did not receive the Medical Cooling Concession. By contrast, householders were acutely aware of

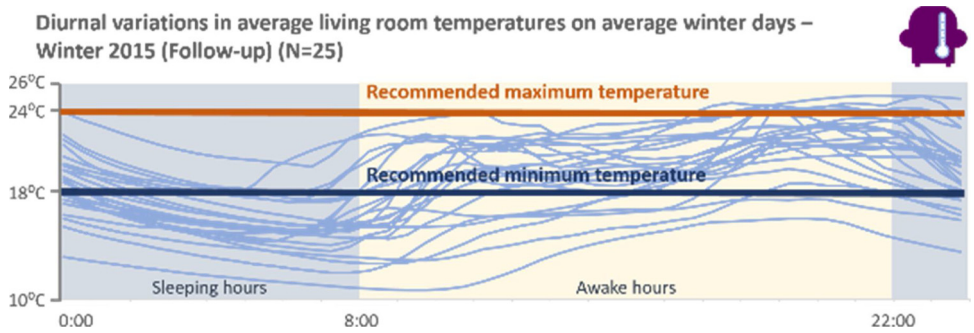

Fig. 13. Diurnal variations in average living room temperatures on average winter days – Winter 2015 (Follow-up) (N = 25).

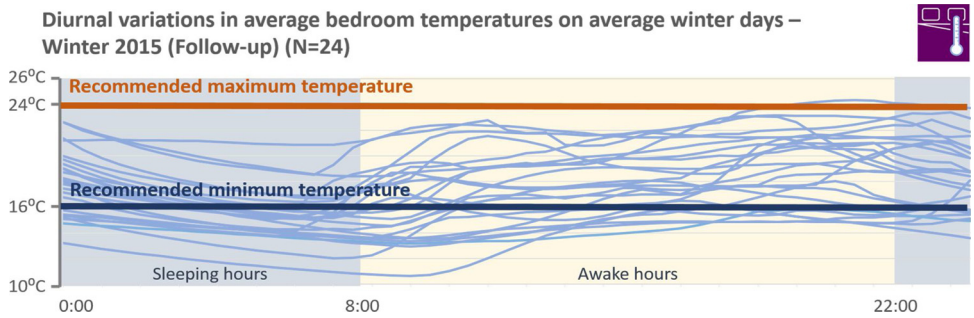

Fig. 14. Diurnal variations in average bedroom temperatures on average winter days – Winter 2015 (Follow-up) (N = 24).

Fig. 15. Sheet at the bottom of a door for draught proofing representing a tripping hazard. Source: First author.

Fig. 16. Example of an electric fan heater in the bathroom representing an electrical risk. Source: First author.

the energy providers' pay-on-time discounts, and a few households compromised on food to take advantage of this offer. Direct debt and fortnightly pre-payments ('bill smoothing') seemed to ease financial and emotional stress. The reduction of electricity consumption costs by solar

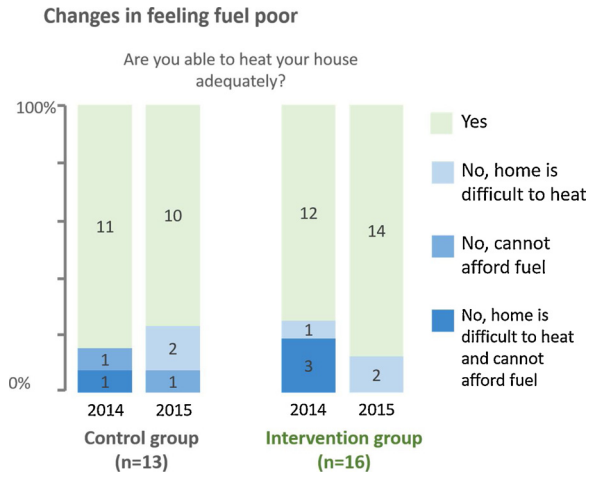

Fig. 18. Feeling fuel poor by study groups and study periods.

photovoltaic (PV) micro-generation in a few households was well appreciated.

Only few householders actively engaged in the energy market due to limited technological capabilities to navigate online price comparison tools and unsure negotiation skills. Failing auditory and visual acuity prevented negotiations over the telephone and the reading of the fine print on the bills. A slight shift towards payment by direct debit occurred during the study and eased bill related stress. Three control and three intervention households changed their energy providers and obtained better discounts in reaction to dissatisfaction with their bills. Three more householders had been granted the Medical Cooling Concessions. Nonetheless, a few householders continued to cope with high bills by trading fresh food or social activities for warmth. The installation of solar PV systems was desired by a few households, however the high capital costs and uncertainty about being able to meet re-payment schedules deterred them from undertaking such upgrades.

> We have been told by one of the solar panel fellas that came from England in the same area as we come from. [Laughter] He's very honest with us. He asked us our age, and we told him, and he said it

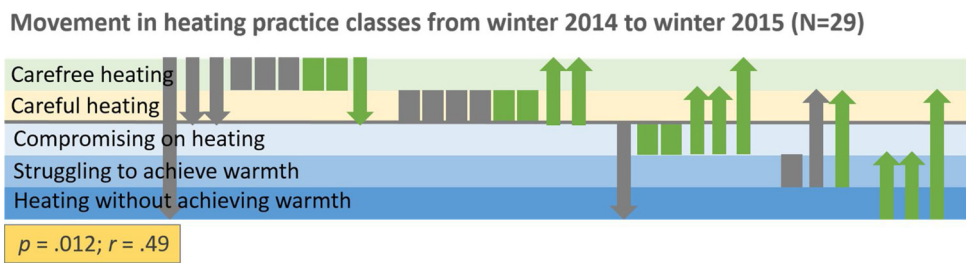
Movement in heating practice classes from winter 2014 to winter 2015 (N=29)
Carefree heating
Careful heating
Compromising on heating
Struggling to achieve warmth
Heating without achieving warmth
p = .012; r = .49

Fig. 17. Changes in heating practice classes from winter 2014 to winter 2015 (N = 29). Positive changes are represented by an upward arrow, negative ones by a downward arrow down. Every green arrow represents an intervention household, every grey arrow a control home.

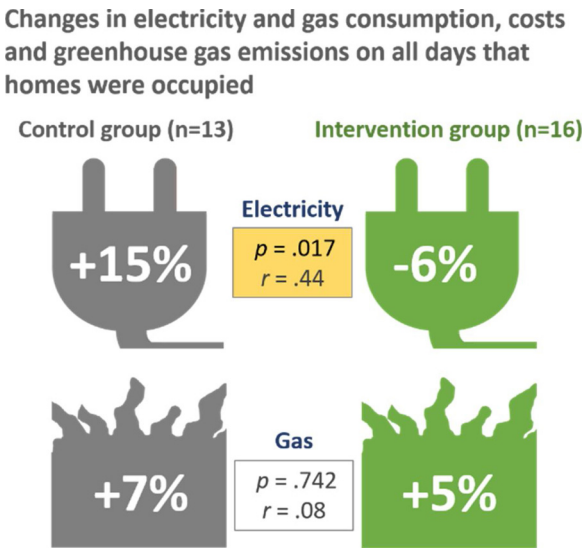

Fig. 19. Mean changes in electricity and gas consumption, costs and greenhouse gas emissions on all days that homes were occupied.

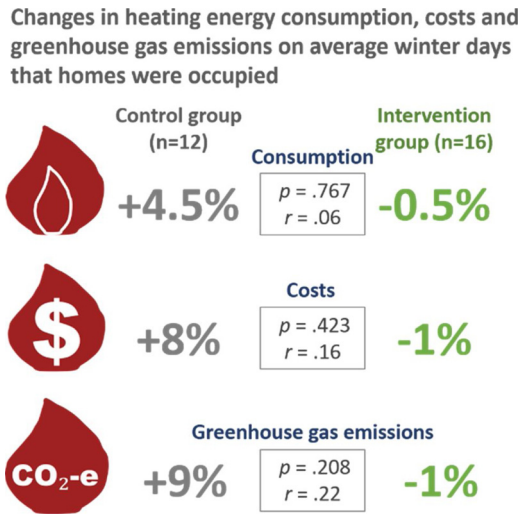

Fig. 20. Mean changes in heating energy consumption, costs and greenhouse gas emission on average winter days that homes were occupied.

would not be worth it anyway, because, you know, how long do you have to live before it pays off. We could not afford to pay it instantly. And he said it wouldn't be worth it. (Lara, age 76, control group)

4.3. Maintaining indoor air quality

The intervention appeared to have slightly reduced involuntary air exchange between the indoors and outdoors with probable benefits in energy conservation and warmth and little apparent risk for moisture-related health risks. Vapour pressure excess was calculated for the 12 living and 12 bedrooms with valid pre-and post-retrofit indoor temperature and relative humidity data. Absolute vapour pressure excess levels in both groups during the follow-up winter were lower than in the first winter in both study groups. This may have been due to the time- and heating-based dependency of vapour pressure excess in dwellings and moisture buffering from furniture [100,101], as householders had started to heat their homes earlier in the colder autumn of 2015 than in 2014. It may also have been the result of failing draught proofing strips or deliberate ventilation.

The study found a practically, but not statistically significant lower

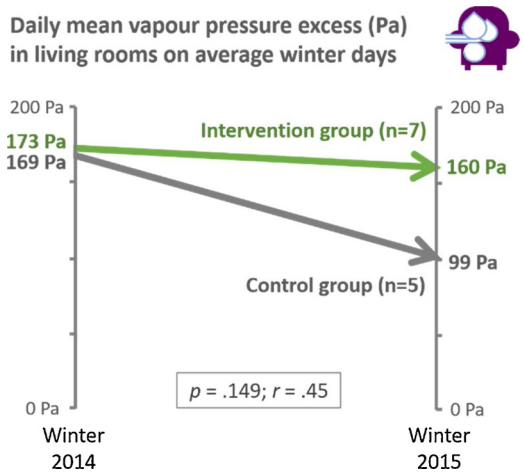

Fig. 21. Mean changes in daily mean vapour pressure excess in the living rooms on average winter days.

reduction in vapour pressure excess in the living rooms of the intervention group when compared to the control group (Fig. 21), although the incidental air infiltration rate had been reduced by an average of 30 per cent. This suggested that draught proofing and insulation may have made the intervention homes practically more airtight. The less than expected change was due to householders not engaging in the assumed practice of rush ventilation. Instead, most householders provided at least some background ventilation through windows being intentionally left ajar (Fig. 22) or through permanently vented bathroom windows (Fig. 23).

Carol: You can't shut it because the sliding little window is below it. (laughter) It's built in, this sort of mesh.
Chris: It's only to get rid of the odour.
Carol: Yes, it's necessary. And then it's sort of have fresh air coming in.
(Carol, age 79, and Chris, age 76, intervention group)

There was no effect on daily mean bedroom vapour pressure excess (Fig. 24), due to the common practice of leaving windows open and due to the internal sealing of permanently vented bathrooms as part of the retrofit measures, which inhibited moisture ingress. Due to low occupancy rates and the common practice of having windows or doors open, most homes presented comparatively low internal moisture loads even after they had been draught proofed. Hence, the prevalence of mould and condensation remained low, being restricted to poorly ventilated areas behind curtains and on the cold surfaces of the single glazed windows.

I hate heating the bedroom. Once you are in bed, you are warm, and you are fine. [The bedroom window] is not ajar, it is not open a lot. Just a little bit. [About 5 cm], that is all. And it has got curtains. I pull the curtains across. So that will stop the draught from coming in a little bit. (Felicitas, age 82, intervention group)

4.4. Living at home

Householders had lived in their homes between 1.5 years and their entire lives. Twelve of the households had downsized into the present home, and a few of these felt that their current homes were too small to entertain. In choosing the houses, participants had placed priority on the accessibility of the house, the garden and the number of rooms. Privacy, quiet and the thermal comfort or energy efficiency of the house were mentioned second in importance. Three households had invested in energy efficiency at the time of moving, yet many householders had no or limited experiences with retrofits prior to the study.

Fig. 22. Example of living room window considered to be open (left) and closed (right). Source: First author.

Fig. 23. Example of a permanently vented window with a mesh insert in a toilet room. Source: First author.

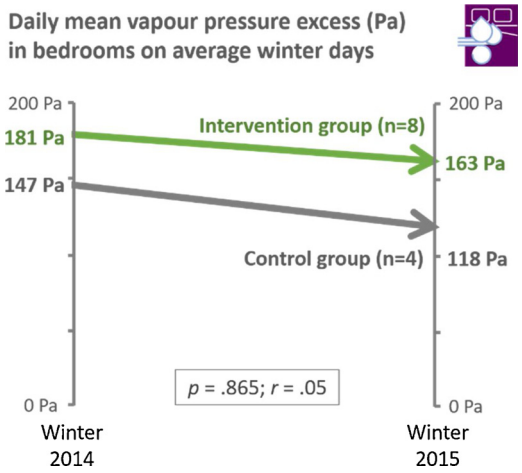

Fig. 24. Mean changes in daily mean vapour pressure excess in the bedrooms on average winter days.

The householders' perception of the psychosocial benefits of the home, namely privacy, freedom, the home as a retreat, status, control, progress, security, routine, safety and identity, and changes therein,

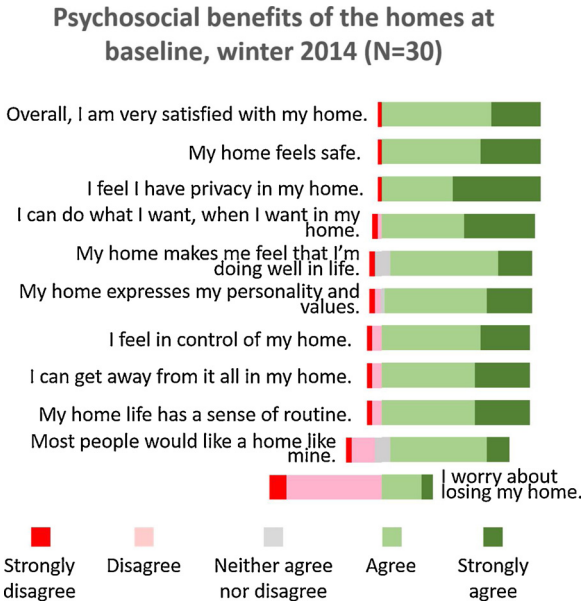
Psychosocial benefits of the homes at baseline, winter 2014 (N=30)
Overall, I am very satisfied with my home.
My home feels safe.
I feel I have privacy in my home.
I can do what I want, when I want in my home.
My home makes me feel that I'm doing well in life.
My home expresses my personality and values.
I feel in control of my home.
I can get away from it all in my home.
My home life has a sense of routine.
Most people would like a home like mine.
I worry about losing my home.
Strongly disagree
Disagree
Neither agree nor disagree
Agree
Strongly agree

Fig. 25. Assessment of psychosocial benefits of the homes at the baseline.

were assessed by the ten rating statements developed by Kearns et al. [102,103]. Additional questions addressed the perceived beauty of the home and the enjoyment of inviting guests. At the baseline, the householders' perception of their homes' psychosocial benefits was positive in both groups (Fig. 25). Nonetheless, the post-intervention assessments showed a slightly bigger improvement in the intervention homes than in the control homes for almost all elements.

A statistically significant benefit was revealed for the element of control, suggesting that the retrofits enhanced the householders' perceived ability to shape their home environment to their own wishes (Fig. 26).

The intervention had the least effect on the householders' ontological security, which was shaped by concerns about their failing health:

> We live in the most beautiful place, but we have to realise, we've now got limitations. So maybe we might move. Not immediately but we have to be aware. (George, age 79, intervention group)

The intervention appeared to have had a medium size effect on

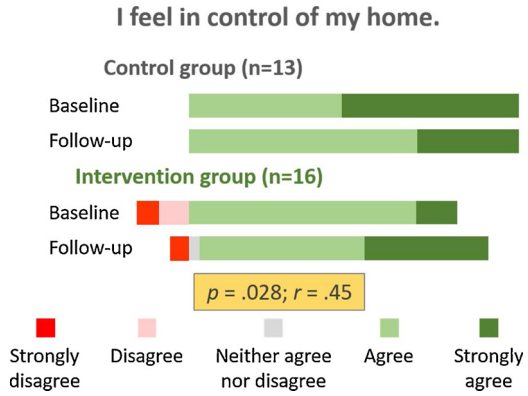

Fig. 26. Assessment of perceived control over the home environment at baseline and follow-up periods by study groups.

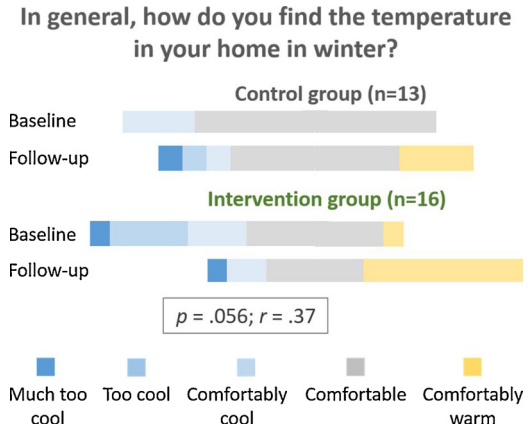

Fig. 27. Subjective assessment of indoor temperature in general at baseline and follow-up periods for both study groups.

winter temperature comfort votes for the home in general, although the *p*-value did not reach the statistical significance threshold of .05. Clinical significance in improving general temperature comfort votes to a 'comfortable' level was found in four intervention homes (Fig. 27). The pronounced decline in winter comfort in two control households was explained by the emergence of fuel poverty and the cessation of heating due to the loss of a spouse and associated income in one home and by increased sensitivity to a cold, unheated bathroom in the other.

The positive shift in perceived difference in temperature comfort of the living rooms and bedrooms in the intervention group was statistically significant with large effects (Fig. 28). The shift in comfort was more pronounced for the living rooms than for the bedrooms, as many bedrooms were not heated. The improvement in room specific comfort may have been shaped by the householders' social desirability bias, as uncertainty hedge words during the conservation such as "probably" and "I suppose" highlighted that some householders referred to the likely, rather than a verified, improvement in comfort. In other cases, the improvement in comfort may have been due to the reduced temperature differentials within the rooms due to the insulation of the building envelope.

Many householders attributed the gain in comfort to the retrofit measures, which they felt had made the homes "cosier" and "warmer", reduced draughts, accelerated the warming of the house and facilitated the conservation of warmth. However, a few householders did not notice a difference in temperatures. Two intervention households complained of a greater unevenness of temperatures throughout the house. This outcome was explained by higher temperature increases in the living rooms than in the bedrooms, the location of an only thermostat in a west-facing kitchen and the influence of radiant temperature. Where a

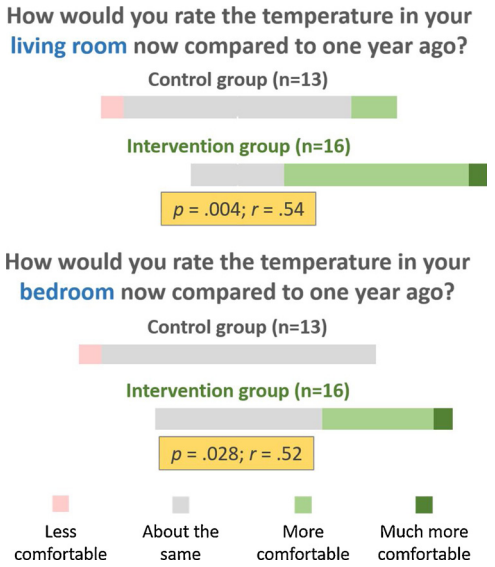
How would you rate the temperature in your living room now compared to one year ago?
Control group (n=13)
Intervention group (n=16)
p = .004; r = .54
How would you rate the temperature in your bedroom now compared to one year ago?
Control group (n=13)
Intervention group (n=16)
p = .028; r = .52
Less comfortable
About the same
More comfortable
Much more comfortable

Fig. 28. Subjective assessment of living room and bedroom temperatures at baseline and follow-up periods for both study groups.

new reverse cycle air conditioner was installed, householder attributed any benefits to the new heating device rather than to new insulation and draught proofing.

4.5. Staying healthy

Householder practices for staying healthy at home primarily concerned accessibility, safety and mould. Householders seemed to have had a limited awareness of the links between cold homes and health and showed more concern about hot homes in summer. Heating as a medical lifestyle prescription was absent in all except one household. Even in those households, in which a cardiovascular event had occurred during the study period, doctors had not enquired about or recommended warmth in the home.

Health outcomes were predominantly assessed through the Australian version of the self-reported health survey SF36v2® with a four week recall period. The difference in score changes suggested benefits for the intervention group in six of the eight health domains, but the effects were small and not statistically significant (Fig. 29). Possible explanations were the suitability of the questions to this sample of householders, most of whom had chronic diseases and impaired mobility. The interviews and comments of the householders during the administration of the questionnaire revealed that other issues such as the health of family members and friends had a stronger influence on their physiological, mental and social health than perhaps a small change in temperature may have had.

> The only difference in that we socialise is that you come and see us. (Darcy, age 75, intervention group)

Most householders accepted their deteriorating physical health with humour, assessed their health with reference to changes in their medication and compared themselves down. Even leading questions proved unproductive. The majority of householders explained perceived effects of the intervention on their physiological health with benefits in awareness, security and comfort rather than with the expected relief in pain, respiratory or cardiovascular symptoms.

4.6. Participating in the study

The majority of householders did not consider themselves to be disadvantaged in income or heating. The success in the recruitment and retention of participants as well as in the acceptance of the retrofits was

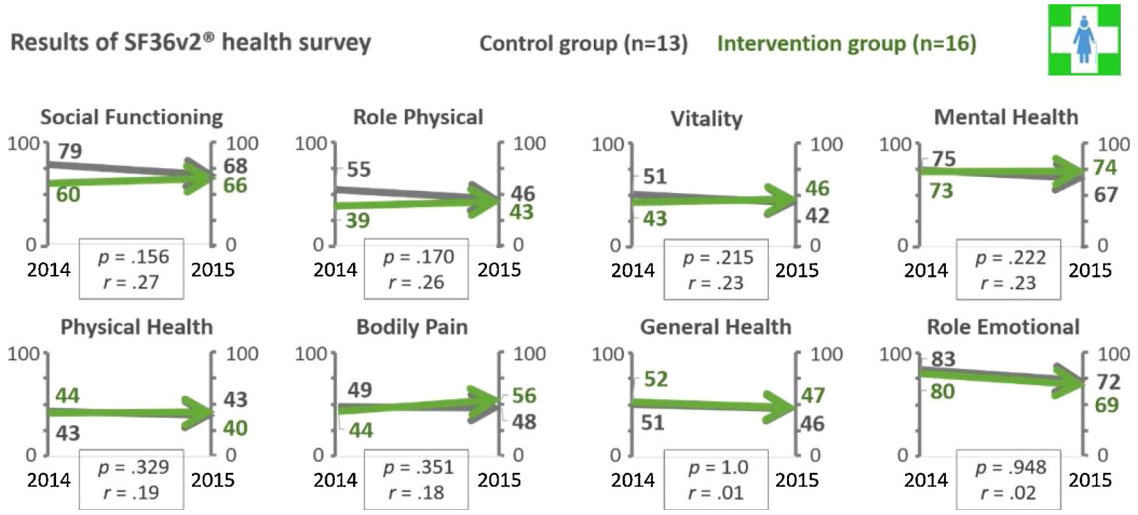

Fig. 29. Changes in SF36v2 scores.

built on the trust that already been established by the councils' home care services. No participant reported to have been motivated to join the study by the prospects of an improvement in health or winter warmth.

For over half of the intervention households, the best aspects of the study were the prospects of comfort, cost savings and the benefit of retrofit measures they would not have been able to afford themselves. Householders welcomed that the LED lights were brighter than the previous light bulbs. The study had also raised the householders' knowledge of energy matters and changed their practices, for example through incidental witnessing the Blower Door Tests, despite the study not including an educational component. The appreciation of new knowledge was equally strong in the control group. Several householders were looking forward to the results of the data analysis for their own home.

Although householders forgave occasional retrofit mishaps, householders did not refrain from showing discontent. Participants complained about sealing strips that peeled off again, unpainted timber sections (Fig. 30) and front doors that opened by themselves after having been draught proofed.

In the control group, the majority of householders valued the social aspects of the study, i.e. the interaction with the research team, the most. The finding that two householders in the intervention group thought that the best part of having been part of the study was meeting the team, highlighted the social isolation of many participants and the quality of the research group.

Incidents of social desirability bias in the householders' assessment of comfort were found, confirming that, in housing intervention studies, subconscious and affective enhancements in evaluating the benefits have to be taken into account. Incidental benefits for health with immediate effect were the removal of polluting gas heaters and other safety measures as a result of the pre-study home audits and the empowerment of householders towards energy providers and tradespersons.

Fig. 30. Example of unpainted timber section as part of he draught proofing of a front door. Source: First author.

> The safety switches were not safe. They just stopped working. So, for me, you know, that was a potential life saver. And, the gas man went around to each outlet and tested the carbon monoxide. […] So as I said, the really practical, on the ground, trades assessment, to me I would contribute to the study, just for that. [laughter] (Sarah, age 55, intervention group)

5. The systemic nature of residential energy efficiency and health

In this study, knowledge of the householder experience provided insights into the influence of householder practices on health and health-related outcomes and demonstrated the links between the thermal quality of the dwelling, householder skills and health status and the meanings of warmth and affordability of fuel. The explanations of the quantitative outcomes of the retrofits showed that the system encompassing the dwelling, the householders, the affordability of fuel and health was dynamic and in constant flux, shaped by and shaping householder practices. Hence, the system of residential energy efficiency and health (Fig. 31) was made up of a complex of social practices [64] that were the expression of the physical materiality of the dwelling, householder competences and the meanings householders attributed to practices and outcomes.

In this cohort of older or frail people, living at home represented a set of social practices connected to the pursuit of health. The dwelling as a material entity provided the setting for the health-related, intersecting complex of practices of heating, ventilation, managing energy contracts, home improvements and the daily negotiation and interplay of these practices. The study confirmed that the perceived affordability of fuel shaped heating practices, yet that the management of energy contracts was an important factor in the experience of fuel stress. Whereas heating patterns and the energy-related quality of the dwelling influenced the heating energy consumption, the affordability of fuel was a function of the amount of consumption, micro-generation, supply charges, pay-on-time discounts, concessions and the budget that was available for energy expenses. The management of energy contracts was influenced by the householders' use of state concession programs and their skills in engaging in the energy market. The budget available for fuel was determined by householder wealth, a function of income,

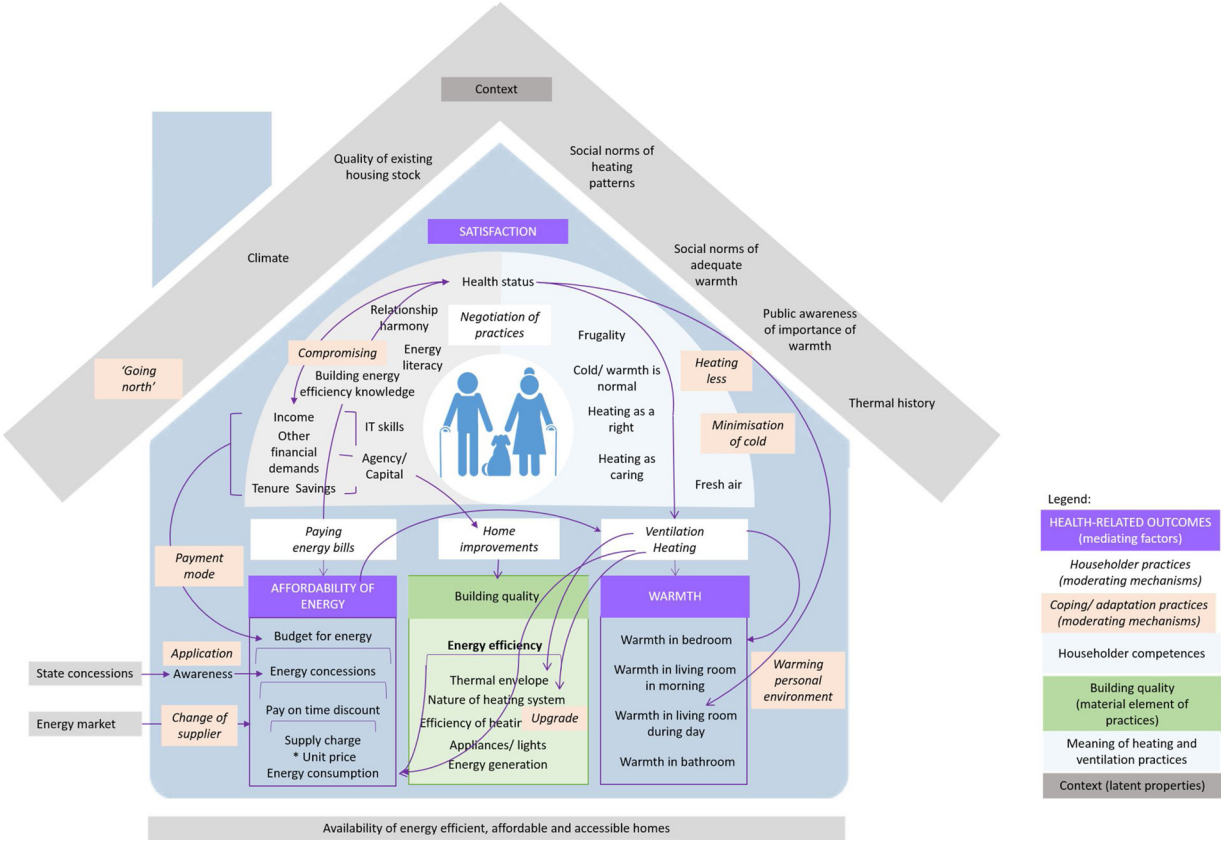

Fig. 31. Diagram showing the system that consisted of the physical materiality of the dwelling, the competences of householders, householder practices influencing outcomes, adaptation practices, health-related outcomes and the context. Arrows indicate the direction of influence.

savings, tenure and other financial demands, which in turn shaped the ability and agency to improve the home.

Health status affected the householders' physiological and financial capacities. Heating and ventilation patterns shaped the warmth in the home, which needed to be differentiated by rooms. Ventilation practices affected the thermal performance of the building envelope and the efficacy of the retrofits. Thermal biographies, acute illnesses and social expectations provided meanings. Deteriorating householder health proved a mechanism that increased residential energy consumption. The accommodation of pets emphasised the role of non-human social relations in domestic practices. Important householder competences were the know-how of using energy in and around the home, householder expectations of the outcome of heating as well as the awareness of the importance of warmth. Satisfaction of the householders with their homes was largely shaped by the perceived norms of adequate heating, warmth and building quality. Coping practices and adaptation in response to the cognitive or subconscious evaluation of the indoor temperatures, air quality or space conditioning costs moderated the exposure of householders to cold and financial stress.

6. Discussion and conclusion

Using a socio-technical framing and a pragmatic, mixed-method design, this study has evaluated the energy retrofits of homes with poor thermal quality of 29 older and/or frail people in Victoria, Australia, explained the effects on indoor temperatures, affordability of energy, psychosocial benefits of the home and householder health, and provided detailed knowledge of the social context for observed outcomes. The knowledge of the householder experience extended the framework of the pathways from housing quality to health outcomes beyond the material qualities of the dwelling to include individual and contextual mechanisms. Amongst others, these were the physiological capabilities of the householder, the modes of energy bill payments, ventilation practices and the social construction of the adequacy of indoor temperatures. In addition, the study has identified coping and adaptation practices that may build resilience. The detailed exploration of the influences of householder practices on the mediating factors of indoor temperature and affordability of fuel, as well as the identification of moderating coping and adaptation practices has helped to better understand the variability of cost, temperature and health outcomes of residential energy efficiency interventions. The weak effect of the intervention on health outcomes between the groups was not unexpected considering that few previous studies, even those with parametric samples, had been able to provide statistically significant evidence for short term health improvements when using self-reported health questionnaires [17,104]. The wellbeing benefits shown in this study concurred with other studies in cold climates [17,104,105]. In contrast to other studies which encountered reservations when targeting retrofits at older householders [49,106], here the existing trust in the home care providers encouraged the uptake of retrofit offers. The findings of the study were limited by the restriction to short term impacts, limited indoor temperature data, the use of subjective health outcome measures and the lack of blinding of participants and the researcher. A confirmation study with a larger cohort and the exploration of outcomes during summer conditions and effects on chemical indoor pollution is recommended.

Nonetheless, the study has revealed some important links between the related practices of keeping warm and managing energy bills, a topic that is gaining traction in the literature on energy poverty [107,108]. It has also highlighted the influences of structural and societal mechanisms that seemed to be particular to the Australian context, such as the prevalence of cold indoor temperatures even in homes of people who may not be financially disadvantaged [109–112], and the observed greater concerns about health effects of indoor heat rather

than indoor cold [113]. This perception contradicts the pronounced winter peak in seasonal deaths [114] and the attribution of this peak to shortcomings in heating [115,116]. However, other practices found in this study seem to be also common in other countries, including the avoidance of winter by travelling to warmer regions [117], and excessive ventilation that counteracts retrofit and health objectives [118,119].

This study has provided a better understanding of residential energy efficiency and health as a socio-technical system and has asserted the role of householder practices and contextual influences on residential energy efficiency intervention outcomes. The study showed that small retrofits may mitigate the growing energy demands of the ageing population group, provide better comfort and reduce greenhouse gas emissions. The effectiveness of the retrofits was reduced by socially shared heating and ventilation practices that contradicted engineering assumptions. The limited statistically significant results proved that the retrofits did not automatically predict benefits and justified the holistic approach that had been chosen to investigate the effects of the intervention. The findings support the call for a systems approach in programs aimed at improving the performance of buildings and social outcomes [120].

Although this paper is based on a case study in Australia, it contributes to debates in other locations through three implications for the integration of equity and health as goals into low carbon transitions. Firstly, the protection of vulnerable people may entail trade-offs with carbon emission reductions targets. The pre-bound effect and persistent underheating highlighted that concerns for social equity and health may have to take precedence over environmental aims, particularly if health becomes more of a priority. Considering that low-carbon transitions are oriented towards the goal of reducing greenhouse gas emissions [121], rises in energy consumption after retrofits may be interpreted as a failure. In the context of health and equity, though, rises in energy consumption that are linked to more adequate indoor temperatures and improved wellbeing of vulnerable population groups should be interpreted as positive outcomes. Such conflicts in the evaluation of outcomes call for interdisciplinary collaborations and the development of a shared vision in energy and health policies.

Secondly, a holistic intervention approach that addresses the interdependencies among quality of dwellings, householder practices, health status and capabilities of engaging with the energy market may be more effective than providing retrofits in isolation. The study empirically illustrates the socio-technical system of residential energy efficiency and health. The system highlights that health co-benefits through retrofits are not merely a technical challenge, but that they need a comprehensive strategy that include householder practices and some of the cultural meanings that may confound or support expected health-related outcomes from retrofits. The paper provides a map or visual tool for a reflexive investigation of the links between general householder practices, adaptation practices, building elements, contextual conditions and health-related outcomes (Fig. 31). In keeping with the pragmatic epistemological stance, this map is useful in its specificity for its given location, time, quality of homes and population group. However, given the importance of health in the promotion of equitable low carbon transitions, the map demonstrates the complexity of conditions that may guide discussions and synergetic efforts across disciplines, practices and policies elsewhere.

Thirdly, collaborations between energy, housing and health programs may facilitate access to vulnerable population groups and the implementation of measures. This study has shown that trust in home care providers encouraged the uptake of energy efficiency initiatives, and that synergies in energy and health programs may advance climate change mitigation efforts. The current Australian Ageing in Place policy and programs do not include such energy-related services. Integrating energy efficiency and hardship initiatives into the services that support older Australians to live at home independently promises to normalise retrofit activities and to change the meanings of retrofits from benefiting the environment to also caring for people. Framing retrofit activities around the benefits of warmth, energy costs, control and safety may shift the perceived significance of energy efficiency improvements from greenhouse gas emissions reduction to that of comfort, affordability of fuel and satisfaction with the home. In addition, increasing the availability of energy efficient and affordable homes and providing householders with information and support with retrofits when they retire or before they downsize may assist in establishing new norms for housing quality for older people.

In conclusion, this study has asserted the role of householder practices and contextual influences on health and health-related outcomes from residential energy efficiency interventions. The study proposes that an effective transition strategy in the housing sector, which aims for triple benefits in carbon mitigation, equity and health has to address not only the practice of retrofitting, but also of protecting vulnerable groups, selling energy and promoting health. Technical interventions may appear to be easy solutions, yet humanistic reflections on the meanings of a dwelling as a home and an alignment of housing, energy and health policies and programs may result in more effective transition strategies for just, healthy and low carbon outcomes.

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